TWO DECADES OF RESEARCH DEVELOPMENTS IN BUILDING DESIGN

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SUMMARY

Although computer hardware has evolved at an unprecedented rate over the last twenty years followed by waves of new software approaches such as artificial intelligence, object-oriented programming and the Internet, research priorities in building design identified twenty years ago are still relevant today. These priorities are: a) to better integrate and share information produced by the various professionals in a building project, and b) to provide assistance to designers earlier in the process when the most important decisions are taken. A review of illustrative and relevant research projects undertaken by the authors is provided in light of these priorities. The main goal behind these projects has always been to produce better buildings, which have such an important impact on people's quality of life, their communities, and the environment.

INTRODUCTION

Computers and applications of IT in construction have been around for much longer than 20 years. Research developments in the field of building design, or Computer-Aided Building Design (CABD) as it is often termed, have however gathered significant momentum and explored many avenues worldwide since that time. Starting from where IT applications in construction stood two decades ago, and more specifically from the identification of important research agenda items in CABD, it is pertinent now to consider developments that have taken place in building design over that period. Such consideration will make it possible, on the one hand, to evaluate what has been attempted and accomplished, and on the other hand, to appraise the relevance of the original research agenda today in order to define promising research directions that could guide developments in the foreseeable future.

It is important to point out that this paper is intended to be more reflective and prospective than merely reporting on the facts and outcome of specific research projects. Following a first section that sketches computing advances that enabled developments in CABD, a second section presents a selection of representative research projects over the period. Common themes in design research philosophy that emerge from this account are presented, thus leading to the determination of research avenues that are most likely to yield significant advances in the future. No attempt is made in the following to provide an exhaustive account/history of research projects or computing developments, but rather to identify trends from projects primarily associated with the authors. It is our belief that such trends are typical of IT research developments in construction elsewhere over the period.

ORIGINAL CONTEXT

Applications of IT in construction can be traced back to the very early days of computing fifty years ago. By the mid-50’s, theoretical developments of the matrix stiffness method enabled researchers to cast complex structural engineering problems into sets of simultaneous algebraic equations that were relatively easy to code and solve by algorithmic programming. By the end of the decade, the concept of discretization made it possible to analyze natural phenomena over continuous domains and to break them down also into simultaneous equations. The foundations were laid out for the development of powerful numerical techniques that are routinely used today like mathematical programming, the finite difference method and the finite element method (FEM), as well as for the emergence of the first commercial computer programs for use in construction like COGO, STRESS and STRUDL.

Through the 60's and 70's, developments accelerated on numerous fronts. On the hardware side, more powerful and efficient processors, thanks to miniaturization and large-scale integration replaced giant energy-wasteful machines. Such a technological evolution pace, characterized by Moore's Law, had never been seen before and quickly resulted in increasing speed and power, cost reduction, thus wider hardware availability. Software technology did not evolve however as quickly. First generation machine language codes gave way to successive generations of higher level computer languages that made it possible to write programs more easily than before. In the field of computer science research called artificial intelligence (AI), developments were targeted at specific thought processes (e.g. natural language processing, artificial vision, game playing, symbolic reasoning) and finding ways to reproduce these with a computer. Considerable efforts went into facilitating the use of computers by human beings, thus generating successive advances in user-interface by means of punched cards then time sharing through monitors and typing, direct data entry with various devices (digitizing tablet, electronic pen, mouse), output in the form of printout, graphic displays, a variety of plotters etc. Finally, the domain of application software development exploded literally producing prototype software - sometimes commercial packages - for a multitude of organized tasks in specialized fields. In the area of buildings and construction alone, Mitchell (1977) reported for example a large number of applications software, mostly at the research prototype level, for tasks as diverse as generating designs and space needs analysis, drafting and analysis of plans, structural analysis and cost estimation, Standards processing and energy/acoustical/lighting analyses.

Situation in Building Design Research

At a symposium (CBS 1981) held at the Centre for Building Studies, Concordia University in May 1981, prominent guest speakers from North America and Europe addressed the theme of 'CABD: Building into the Future'. One category of applications that received a lot of attention at the time was automated drafting packages or CAD (Computer-Aided Drafting). Speakers emphasized productivity gains in construction that would be realized through a large scale adoption of CAD packages because of such advantages as time savings in corrections, greater accuracy and repeatability in presentation and drawing details, ease of communicating construction documents with others working on the same project.

They also speculated on the future of CABD and the necessity, in order to realize significant productivity gains in construction, of developing approaches that can:

a) **integrate the contributions of different specialists** collaborating on the same project, and

b) **help designers effectively as early as possible** in the design process since the most influential decisions on the overall performance of buildings are made at that stage.

In spite of the general optimism regarding the potential benefits of computing in building design, some speakers expressed concerns about the very low rate of penetration of IT in construction firms, due in part to the prohibitive cost of hardware and the difficulty in making a cost-effective use of software in real projects. Even in the specialized field of structural engineering where computing had been embraced and continuously refined from the early days, Fenves (1998) reported that the prevailing use of IT up to the mid-80's was in custom programming by individual engineering firms.

Such was the situation in building design research twenty years ago. Basically, the feasibility of using novel IT tools and techniques had been amply demonstrated in a number of areas but these remained very specialized, thus restricted in scope, awkward to use given their prototype nature, and finally prohibitively expensive to acquire, use and maintain because of the scarcity of computing resources (including computing personnel).

Momentous changes

Two events taking place around that time had a major impact in stimulating CABD research. The first one undoubtedly was the democratization of computing realized by the advent of the personal computer (PC). The introduction of the first IBM-PC in August 1981 is often referred to as the lead event, even though other PC's had been introduced on the market a few years before. Not only was the PC affordable by individuals and small organizations, but it was also relatively easy to use by non-specialists because of simpler operating system and programming environment. Twenty years later, a survey was conducted (Rivard 2000) to provide a snap shot of the status of IT in the construction industry in Canada. It showed that all firms surveyed had computers, 92 % of all architectural or engineering firms surveyed had CAD, and 90% of the firms surveyed were connected to the Internet. The study also showed that, according to the firms surveyed, the two most important research directions were computer-integrated design and construction as well as design support at the conceptual stage, which coincide perfectly with the main agenda priorities identified above to ensure productivity gains in construction.

The second influential change affecting the development of research in building design stemmed from the demonstration that research prototypes in AI could be used effectively in construction. The application of a knowledge-based expert system (KBES) development tool to guide users of a complex FEM package to perform structural analysis gave rise to an advisor system called SACON (Bennett et al. 1978). This prototype demonstrated that other computing avenues than algorithmic programming, namely symbolic programming, could be effectively developed to represent and solve problems in construction that cannot be reduced to a rigid sequence of calculations. A decade earlier, the seminal work of Simon (1969) had provided the theoretical underpinnings for a formal representation and treatment of the design process, in contrast to the prevailing view at the time that design can only be learned by experience. Design researchers were therefore equipped with a new set of tools and techniques as well as a theoretical basis to capture design heuristics and cast these into a formal representation of the design process amenable to computer processing. In the next section, research developments in CABD over the last 20 years are presented by means of projects at the CBS that are typical of specific development approaches.

RESEARCH DEVELOPMENTS IN CABD OVER THE LAST TWO DECADES

A- Application of AI techniques to capture design tasks and assist designers

SACON had conclusively demonstrated that a generic KBES development tool could incorporate expertise from a variety of domains, to produce specific applications for problem solving in such domains. More importantly, it showed that a new computing paradigm called knowledge-based system (KBS) can be used to capture problems like design that cannot be cast strictly in terms of numbers and algorithms. Typically KBS are made of two distinct components, a knowledge base encoding knowledge as facts/rules/frames, and an inference engine ensuring that reasoning proceeds systematically.

A first project completed by our group (Fazio et al. 1989) exploited the rich encoding capabilities of KBS to help consultants design the building envelope system. The envelope constitutes an essential building system whose primary function is to separate and maintain the living conditions of the indoor environment from being affected by fluctuations in outdoor weather conditions. The design of a building envelope is influenced by a number of factors such as cost, structural, environmental and aesthetic performance requirements which would call for the specialized knowledge of different disciplines (architect, civil and mechanical engineers, material specialist, contractor). In spite of its critical importance and the huge amounts in litigation every year associated with envelope failures (e.g. leaking roofs and windows, condensation in wall assemblies), the design process of the envelope had never before been the subject of a systematic attempt of organization, particularly at the preliminary stage when the most influential decisions are taken affecting performance over the entire life-cycle. A prototype KBS called BEADS (building envelope analysis and design system) was assembled combining a knowledge base that incorporated information from practicing architects, building Codes, performance Standards, design manuals, material properties and cost data handbooks, with a generate-test strategy that could establish the design context, define performance attributes, generate feasible alternatives and evaluate them at the preliminary stage. A mainframe-based development tool called Knowledge Craft was used to develop BEADS, with hybrid knowledge representation based on schemas (frames) and rules to represent procedural and heuristic knowledge in an efficient manner. Figure 1 shows an example of the schema 'Design-Context' indicating input parameters, performance requirements and information sources (Note: NBCC and ASHRAE stand for building Standards). Figure 2 illustrates a feasible design alternative as generated by BEADS with envelope construction details and critical performance attributes that are used to rank alternatives according to preferences expressed by the designer.

BEADS proved capable of handling information during design decision making in situations where knowledge from multiple sources/disciplines is involved, without sacrificing designer's freedom. It could be used effectively by an architect with little technical knowledge of energy analysis or condensation

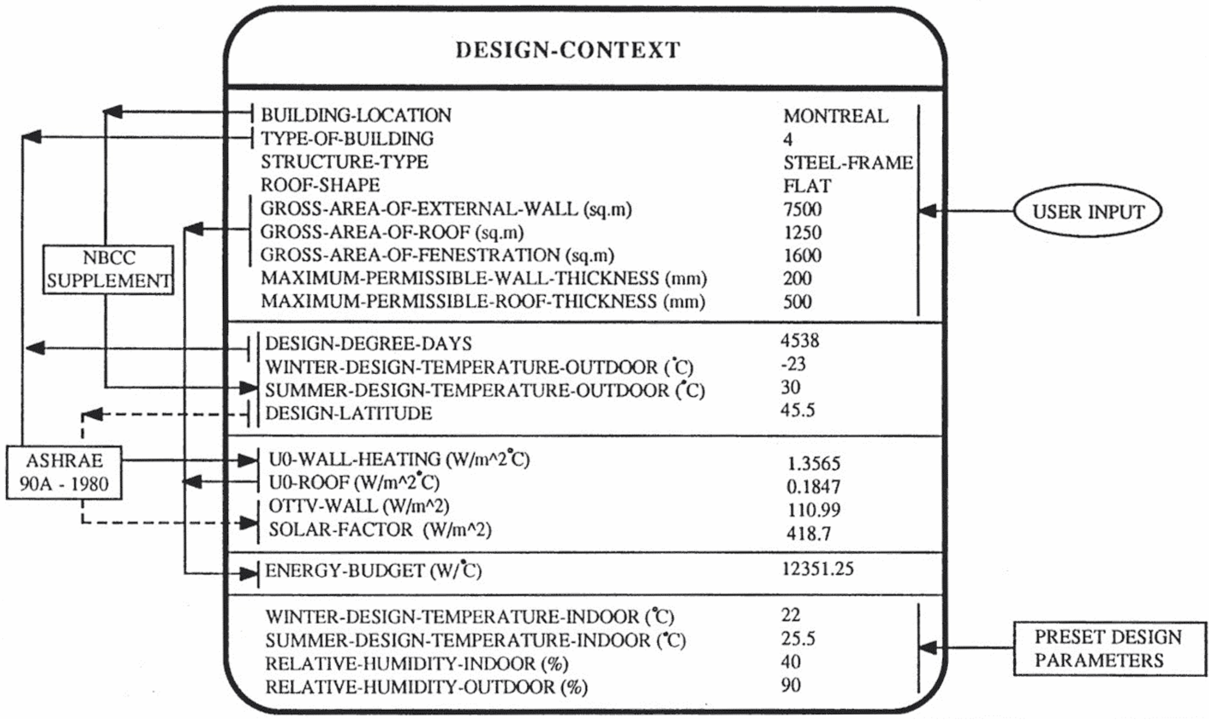

Figure 1 BEADS input: design context and information sources.

calculations, and provided meaningful comparisons between practical design alternatives at an early design stage with little input data. In spite of such advantages, BEADS remained at the 'proof of concept' level with marginal impact on the building design practice, primarily due to the complexity and resources required in using Knowledge Craft. Such restrictions to technology transfer were effectively removed a few years later by means of a spin-off project, which resulted in the implementation of a simple PC-based application that made available to architects the analysis module incorporated in BEADS. A building envelope design tool called CONDENSE (Rivard 1993) was thus coded in AutoLisp as an add-on within AutoCAD. A typical design solution screen is shown in Fig. 3 that exemplifies significant progress made in providing assistance to the designer by means of a graphical user-interface (GUI) when compared to BEADS in Fig. 2. Well over a thousand copies of CONDENSE are now in use across North America, thus proving to be a very effective technology transfer vehicle towards the building design practice.

FEASIBLE-ALTERNATIVE-54		
WALL-TYPE	STUCCO-ON-CONCRETE-WALL	
ROOF-TYPE	BUILT-UP-OR-SINGLE-PLY-ON-METAL-DECK	
INSULATION-TYPE-FOR-WALL	GLASS-FIBRE-BOARD	
INSULATION-TYPE-FOR-ROOF	RIGID-GLASS-FIBRE	
GLAZING-TYPE	DOUBLE-GLAZING	
ENERGY-CONSUMPTION	2701.26	(W/ °C)
MATERIAL-COST	594982.0	($)
TOTAL-THICKNESS-OF-WALL	281.5	(mm)
TOTAL-THICKNESS-OF-ROOF	140.0	(mm)
UTILITY-VALUE	32.3 9.8 1.4 10.6 10.5	

Figure 2 BEADS output of an envelope design: instance of a feasible alternative.

A number of significant CABD research projects have followed at the CBS in the same spirit as BEADS, using AI techniques to capture design tasks and provide effective support to design practitioners. The project of Ravi Mathi led to the development of a KBS to perform the overall configuration of multistory office buildings at the preliminary design stage (Bédard and Mathi 1991). Using a frame-based development tool on PC, the system could generate rectangular floor plans at different levels of detail taking into account multidisciplinary design criteria such as flexibility of rental areas, compatibility with the structural system, general energy efficiency etc. This project resulted in the assembly of a knowledge repository made of numerous design heuristics extracted from a variety of sources, and in the development of a methodology for generating and evaluating space layout alternatives as well as compatible structural system alternatives. It was validated by means of direct interaction with two design professionals, an architect and a structural engineer, who used the system to generate early schemes of office buildings which they had actually designed and built a few years earlier.

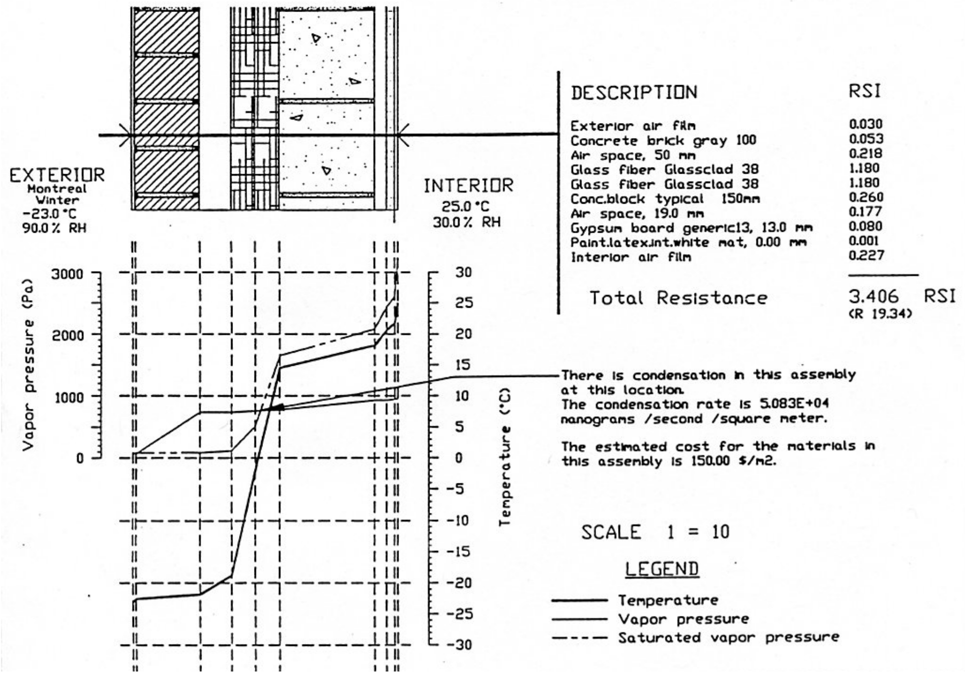

Figure 3 CONDENSE output: design of a wall assembly.

Other noteworthy CABD research projects have tackled specific issues in wind engineering. The evaluation of wind loads on buildings is routinely performed by referring to building Standards, which typically cover only a few common cases of simple isolated buildings in a simplified uniform environment. For other cases, designers must either resort to costly and time-consuming physical testing in a boundary-layer wind tunnel or complex CFD (computational fluid dynamics) simulations. CABD research has provided a third avenue by making available to the designer a wealth of specific wind information obtained by various means (wind tunnel, Standards, CFD, on site measurements, curve fitting) within a computer-assisted environment that provides interaction and advice to the designer. All these projects have produced design assistants for specific wind conditions whereas some have also resulted in additions to building Standards. For example, three projects that are detailed elsewhere made use of: a) KBS and databases to predict and improve pedestrian wind conditions in the vicinity of projected buildings (Wu et al. 1995), b) a hybrid KBS combined with neural networks (NN) to optimize building configurations at early design stages in situations where wind interference effects may be significant (Khanduri et al. 1997), and c) a cascade NN with CFD algorithm to assess the impact of complex terrain conditions on wind loads (Bitsuamlak et al. 2002).

In short, CABD research projects incorporating AI techniques over the last 20 years evolved from using merely a KBS approach on mainframes to combining other computational techniques like NN, CFD and DBMS on PCs. The main research thrust remained however unchanged, focused on enabling the integration of viewpoints/disciplines/information sources to provide effective design assistance to the practitioners at an early stage in solving significant and realistic problems, all elements that were identified 20 years ago as priority research agenda items in CABD.

B- Computer Integration of Design and Construction Information

The construction industry in North America has a level of fragmentation that is unparalleled in other large industries. Typically, a building project brings together a unique amalgam of design firms, general contractors and subcontractors that will never work together again. Fragmentation gives rise to communication/coordination breakdown across project phases, disciplines and subsystems. This old problem was reinforced with the advent of computer applications since these are generally self-contained and unable to communicate with each other. Users are constrained to interpret and transfer data manually between applications: an inefficient, time-consuming and error-prone process. Significant research effort has gone toward addressing this prevalent problem (see Eastman (1999) for an excellent historical account). At the Centre for Building Studies, the integration of the various views of building design has always been of the utmost importance. Bédard (1989) has proposed the '3P model' to provide a means of visualizing how a given research effort is encompassing in terms of integration (see Fig. 4). The model consists of three axes, namely, the product, process and participant axes, which can illustrate in 3D space the several phases, the expertise and viewpoint of the many participants, and the building systems with their many components required to deliver a building.

Another indirect outcome of the BEADS project was the realization that there was a lack of shared data representation that allowed the exchange of information between the various designers involved in the design of the building envelope. An analysis of the data needs during building envelope design led to a proposed representation that would address this hiatus (Rivard et al. 1999). This was followed by the development of a more comprehensive representation that would address conceptual building design (Rivard and Fenves 2000). This unique representation satisfied the following requirements: a) to integrate multiple views, b) to support design evolution, c) to provide for design exploration, and d) to be extensible. Such a representation has features that are lacking in current standardization efforts, like industry-driven IAI-IFCs, CIMSteel, and STEP, which focus on the later stages of design, do not explicitly support design evolution, and define static building representations.

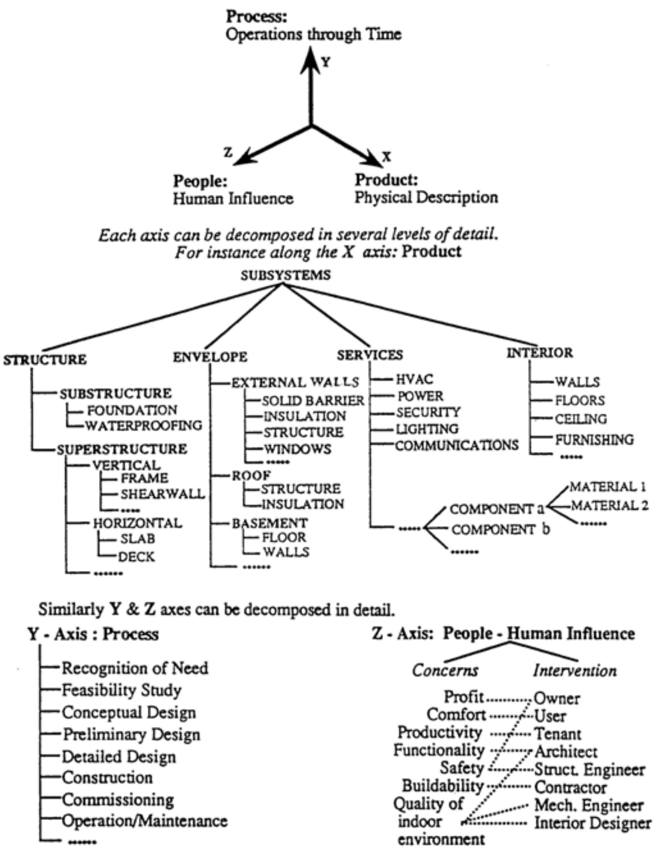

Figure 4 The 3P model, a multidimensional description of buildings.

C- Current work

Even though computers have become ubiquitous in the AEC industry, their present use is mostly dedicated to the later stages of building design when the form of the building is already defined and the main building technologies have already been selected. Computers fall short of supporting design generation since designers must resort to hand-drawn sketches for fleshing out their ideas before detailing them in CAD software. As pointed out above, it is during the early stages of design that major decisions are taken which have the greatest impact on the final form, constructibility, costs, and overall performance of buildings. Yet, the time, people, tools and resources allocated to this phase are very limited. Consequently, designers execute it by intuition and experience rather than by exploring the unbounded space of possibilities in a systematic manner. By using current computer technology, efforts have been made over the last few years to develop tools that would let designers explore this space in a tractable manner (Fenves et al. 2000). The intent of on-going research is to develop a new design environment that can tap the creativity of designers, support them in the early explorations of a wide array of alternatives, foster collaboration among the various designers involved, increase their expertise by volunteering additional knowledge, and provide easy access to knowledge stored within a growing library of past designs. Computers are not meant to replace designers in taking decisions but to assist them in evaluating a wider array of alternatives. Designers are better than computers at dealing with creativity, judgment and esthetics, and since they may be legally liable, design decisions must be left to them. Such new environment will enable designers to do all their work in a user-friendly and intuitive manner to efficiently create original and effective solutions. CABD research at the CBS currently focus on this goal.

A study of eight architects at work was conducted and resulted in a set of specifications for computer tools in early design (Meniru et al. 2003). Such a tool is being developed according to these specifications in order to bring engineering knowledge to architects earlier in the building design process.

Studies have shown that three-dimensional design is more effective for communication because it provides a better representation of the intended facility. A tool for both architects and structural engineers is being developed. The building representation presented above has been expanded to include concerns from architecture (Rivard and Fenves 2000, Mora et al. 2002). This common representation will allow architects and structural engineers to work together in defining volumes and structural systems. Geometric modeling and reasoning capabilities are being integrated to support the elaboration of a structure from the overall geometry and to use functional requirements to develop specific components in 3D. The intent of this research, which is in continuity with the work of Mathi, is to provide on-line collaboration via Internet between structural engineers and architects. The potential benefits are: a) to develop a better understanding of conceptual structural design, b) to formalize structural design knowledge for buildings, and c) to provide a collaborative environment to assist designers at the conceptual stage, which is not currently supported by commercial packages. The approach will introduce computer-supported structural synthesis and design capabilities much earlier in the design process. It will lead to a more efficient and integrated design process resulting in better, more integrated buildings.

CONCLUSIONS: RESEARCH PHILOSOPHY AND FUTURE OF BUILDING DESIGN

Over the past 20 years, annual meetings of CIB W78 have seen the reporting of tremendous developments in CABD research worldwide, as exemplified by the few projects from the CBS reported above. Much progress has been accomplished on many fronts, the most spectacular advances undoubtedly being in terms of hardware availability, capabilities, diversity and ease of use. On the software front, a multitude of approaches/environments have been developed and tested over the period, with focus on drafting 20 years ago gradually shifting to the use of AI techniques, Standards processing and hypertext, product and process modeling that led to international collaboration driven by industry (e.g. ISO-STEP and IAI-IFCs), DBMS and object-oriented programming, World-Wide Web and Internet etc. Although progress in such areas cannot be measured as clearly as for hardware, general trends can be identified everywhere in CABD research developments as going from isolated very specialized applications to environments capable of communicating with others, performing several tasks, and encompassing different concerns, i.e. from specialization to globalization. In other words, one can say that priority agenda items for building design research stated 20 years ago are still as valid and fundamental now as they were then. For our part at the CBS, we have stayed the course with our own design research philosophy, which is fully consistent with the above priority agenda items. Put simply, our long term goal has always been to **produce better buildings.** Since people spend more than 90 % of their life inside buildings at home, work, for entertainment etc., 'producing better buildings' encompasses therefore all types of buildings, under all performance conditions and for their entire life-span. Hence our primary research focus remains **integration** in the broadest holistic sense, as well as developing the means to enable integrative design decision-making **as early as possible** in the process, at a time when decisions have the greatest impact on the overall building life-cycle performance. Our work also endeavors to keep the human designer in charge, and to enable him/her to solve meaningful problems in a manner that is as natural as possible.

Where does the future of building design research lie ? In our view, three main thrusts will characterize future developments in CABD. First of all, building design research will enable greater integration than before, along and across all axes of the 3P model shown in Fig. 4. Second, new approaches will be focussed on augmenting human design capabilities, i.e. approaches that are more user oriented, that enable communications more effectively with others, that take routine out of design tasks in order to focus human intervention where it really provides added value. Finally, a novel building design approach will account for sustainability. The environment has become a priority because the scale and rate of global environmental degradation is the greatest threat of the 21st century. If humanity is to sustain itself, everyone will need to take some drastic measures, as instigated by the Kyoto Accord, to adopt a more considerate way of life. Sustainability can be achieved by concerted and conscious efforts on the preservation of natural resources and the reduction of greenhouse gas emissions through better design of buildings. Because buildings are the primary energy consumers in cold climates like in Canada, research in green-building design is a vital and promising field of research that will lead the way to buildings with higher performance level and smaller environmental impact, taking into account new concerns like embodied energy and gas emissions.

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